# VI.5 Advanced Control Modules for Hybrid Fuel Cell/Gas Turbine Power Plants

*Hossein Ghezel-Ayagh*
*FuelCell Energy, Inc.*
*3 Great Pasture Road*
*Danbury, CT 06813*
*Phone: (203) 825-6048; Fax: (203) 825-6273; E-mail: hghezel@fce.com*

*DOE Project Manager: Magda Rivera*
*Phone: (304) 285-1359; E-Mail: Magda.Rivera@netl.doe.gov*

*Subcontractors:*
*National Fuel Cell Research Center, Irvine, CA*
*Carnegie Mellon University, Pittsburgh, PA*

## Objectives

The overall project goal is to develop advanced and intelligent control algorithms for hybrid fuel cell/gas turbine (FC/T) power plants. The specific objectives are as follows:

- Establish a dynamic modeling environment to facilitate simulation studies, as well as development and testing of control algorithms.
- Increase reliability and availability of the hybrid power system by investigating the application of model-based control algorithms.
- Develop robust controllers that maintain stable operation and high performance of the hybrid power plant.
- Develop optimal control strategies to improve performance and to accommodate fast response during rapid transients.
- Accommodate measurement errors, as well as sensor and actuator faults, to reduce the number of unplanned shutdowns.
- Extend service life of the components in the hybrid FC/T power plant.
- Integrate robust and optimal controllers into an overall supervisory framework.

## Approach

- Develop modular dynamic models of the key system components based on the laws of conservation of mass and energy.
- Develop constitutive equations describing performance characteristics of fuel cell, gas turbine, and other balance-of-plant equipment.
- Synthesize integrated dynamic system models by incorporating key process equipment and controllers in FC/T hybrid power plants.
- Develop robust controllers that maintain stable operation of FC/T systems in spite of environmental disturbances, measurement errors, model simplifications, and incorrect model parameters.
- Employ dynamic optimization routines to improve plant performance and power output while maintaining operating constraints.
- Implement data reconciliation and disturbance estimation techniques in the overall control strategy.
- Develop a feedforward neural network supervisor based on results of optimization studies.
- Develop fuzzy logic techniques to accommodate sensor and actuator faults.

## Accomplishments

- Completed the development of modular dynamic models for internally reformed carbonate fuel cells (Direct FuelCell®, DFC®) and solid oxide fuel cells (SOFCs) as well as microturbines and balance-of-plant equipment using the MATLAB®/Simulink® programming environment.
- Completed integration of sub-MW hybrid DFC/T® and SOFC/T simulation programs based on a 60-kW commercial microturbine generator.
- Refined control strategies for fuel cell stack temperature, gas turbine operation, and fuel feed rate during start-up and power ramps.
- Developed a dynamic optimization modeling environment and initiated FC/T system optimization studies.

## Future Directions

- Linearize dynamic models; use linear process models to analyze plant controllability, to determine optimal input/output pairings, and to develop robust controllers.
- Determine optimal ramping strategies for a diverse set of load profiles via dynamic optimization modeling.
- Develop techniques for disturbance estimation and data reconciliation through optimization studies.
- Develop a neural network framework suitable for online control supervision. Train the neural network with results from the control optimization studies.
- Develop fuzzy logic fault detection and fault accommodation techniques.
- Integrate overall control strategies into the simulation environment for extensive testing of the algorithms for their robustness and stability.

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## Introduction

The control system for fuel cell/turbine hybrid power plants plays an important role in achieving synergistic operation of subsystems, improving reliability of operation, and reducing frequency of maintenance and downtime. The control strategy plays a significant role in system stability and performance as well as ensuring the protection of equipment for maximum plant life. Figure 1 shows a simplified process diagram of an internally reforming SOFC/T system, which is being studied for development of advanced control algorithms. The system is based on an indirectly heated Brayton cycle. The anode exhaust, which contains the remainder of the fuel, is mixed with the cathode exhaust in a catalytic oxidizer, where oxidation of fuel is completed. The hot oxidizer exhaust passes through a heat recovery unit (HRU) in which it preheats the compressed air before entering the turbine. The hot compressed air is expanded through the turbine section, driving an electric generator.

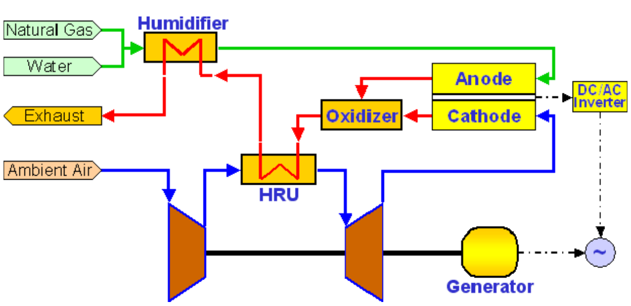


**Figure 1.** Conceptual Process Flow Diagram for SOFC/T System

Dynamic simulation has proven to be a powerful design tool to study the transient behavior of fuel cell/gas turbine hybrid systems. Development of an advanced control strategy is facilitated by using a dynamic model both as a simulation test bed and as part of the controller itself. Components of the advanced control module include a neural network supervisor, robust feedback controllers, and predictive system models. These advanced control components are used in the development and demonstration of an innovative algorithm that optimally controls hybrid power systems, and yet is easily adaptable to the type of fuel used, whether natural gas, coal gas, or digester gas.

## Approach

The advanced control module shown in Figure 2 is based on a feedforward/feedback structure. It

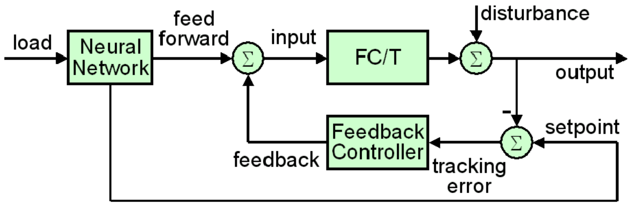


**Figure 2.** Advanced Control Module Comprising Neural Network Supervisor and Robust Feedback Controller

consists of a combined robust controller and a neural network supervisor that together manipulate the actuators to optimally control the hybrid system during load ramps. The feedforward controller will provide optimal dynamic scheduling based on the prescribed load profile and trends. Because the optimization routines are computationally too intensive for real-time application, they will be carried out offline. The resulting data will then be used to train a neural network supervisor. The feedforward controller performance depends strongly on the accuracy of the model employed to tune it. A feedback control strategy is utilized to compensate for setpoint deviations caused by imperfect feedforward control moves. The feedback controller will be designed using robust control techniques.

### Robust Process Control

The approach is to develop low-level controllers suitable for implementation in a standard programmable logic controller (PLC). These controllers will be designed offline using information about the plant and will meet prescribed levels of robust stability and performance. The robust stability will be achieved for both the linear plant model as well as all sets of models corresponding to anticipated uncertainties. Robust performance will be achieved by virtue of exceeding a set of performance specifications (overshoot, rise time, etc.).

### Nonlinear Dynamic Optimization

Feedforward control is typically based on steady-state mappings between the process variables and the controlled variables. To build feedforward action into the feedback-based robust design, the setpoints and supplementary feedforward control signals are found via dynamic optimization. The technique involves minimization of an objective function, subject to Multi-Input-Multi-Output (MIMO) nonlinear plant dynamics and specified constraints. The optimization model involves specification of hard input constraints (e.g., valve limits) and soft output constraints (e.g., functional within bounds). AMPL, a mathematical programming language, will be utilized for implementation of the derived large-scale constrained optimization equations. The nonlinear programming (NLP) solver, IPOPT, will be used for numerical solution of the dynamic optimization model. IPOPT is a state-of-the-art interior point NLP solver that will be used to handle constraints which arise in operation of the actuators in hybrid FC/T systems.

## Results

Development of component models in MATLAB/Simulink has been completed. The models include software programs (modules) for internally reforming DFC and SOFC stacks, microturbine, and balance-of-plant equipment. Integrated system models were developed for both SOFC/T and DFC/T systems based on the component-level models. The modular nature of the computer models in Simulink allows for flexibility in development of integrated system models, as shown in the DFC/T example of Figure 3.

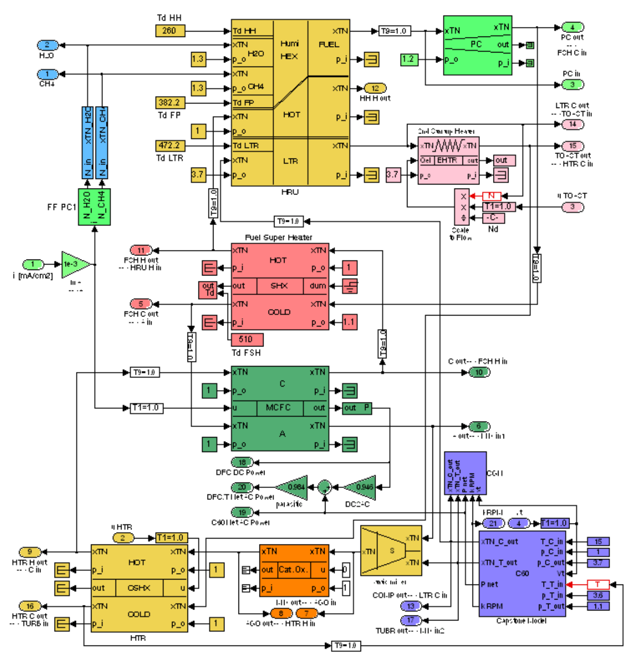

**Figure 3.** DFC/T Dynamic Simulation Model in MATLAB/Simulink

The integrated dynamic system models were utilized to refine the control strategies for start-up of the microturbine and fuel flow, as well as for control of the cathode inlet temperature throughout the operating range. The underlying principle for the developed control strategy is optimization of the waste heat recuperation to maximize the turbine inlet temperature and power generation. The strategy was implemented in the dynamic models to simulate and verify start-up and load operations of a sub-MW class hybrid power plant. The dynamic simulation studies have resulted in improvements of the control system design. As an example, thermal management of the fuel cell stack was improved by manipulating the microturbine speed.

The development of the optimization models based on the AMPL/IPOPT software platform has been completed. Using this framework, optimization is performed, and feedforward control moves and setpoints are scheduled based on the offline optimization results.

## Conclusions

Dynamic simulation models for both DFC/T and SOFC/T systems were developed in MATLAB/Simulink. The models included implementation of plug-and-play sub-models, which are easily connected to configure the entire systems. This modular approach decreased the time required for dynamic system model development and increased the flexibility for investigating system configurations. The developed dynamic simulation models have enabled testing of new system designs, verification of new control algorithms, and integration of system components early in the design phase. Activities are underway to develop a database of load change trajectories to facilitate the training of neural network based controllers.

## FY 2005 Publications and Presentations

1. H. Ghezel-Ayagh, M. D. Lukas and S. T. Junker. "Dynamic Modeling and Simulation of a Hybrid Fuel Cell/Gas Turbine Power Plant for Control System Development", Proceedings of ASME/Fuel Cell Science, Engineering and Technology Conference 2004, ASME FuelCell 2004-2488.
1. H. C. Maru and H. Ghezel-Ayagh, "Direct Carbonate Fuel Cell – Gas Turbine Combined Cycle Power Plant", Presented in European Fuel Cell Forum, Lucerne, Switzerland, July 5-8, 2005.